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<p>A problem has been perceived in diagnostic support for complex modern weapons systems. Each of the services has undertaken development of diagnostic aids to address this need. To evaluate the design of such a device, it is necessary to understand the process of diagnosis and current research in the field of diagnostic job performance aids.</p> <p>The way a diagnostic aid is developed is based upon certain assumptions about how diagnosis is performed, and what types of knowledge the diagnostician needs at the job site. Expert rules and cognitive models are discussed.</p>											
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ABSTRACT

Modern weapons systems rely upon complex electronics for mission essential functions, such as fire control. The repair strategy is to remove and replace a faulty 'black box' (known as a Line Replaceable Unit or LRU) at the forward weapon site, and evacuate it for repair. However, on-board diagnostics and methods available at the owning unit have proved inadequate in isolating a fault to a single LRU. This leads to a strategy of 'swapping' known good components for those in an ambiguity group to return the system to operational status.

The Army's program to solve this identified problem is the Intermediate Forward Test Equipment (IFTE), comprised of a van mounted Base Shop Test Facility (BSTF) for intermediate level diagnosis and repair of evacuated modules, and the Contact Test Set (CTS) and portable tester designed to be employed by the intermediate maintenance support team at the weapon system site when the owning unit has failed to fault isolate to the LRU level with available methods. As such, the CTS is primarily a replacement for existing bulky and unwieldy automatic test equipment (ATE) and inadequate troubleshooting procedures contained in technical manuals.

The BSTF is used in a bench test environment, and it is possible to apply human factors standards (for example, those in MIL-STD-1472) to these workspaces (such as a shop repair van). However, such is not the case for portable computers (such as the Contact Test Set) to be used at the weapon system site: for some supported weapons systems, this will be outdoors, with the CTS positioned on or about the weapon system. In addition to such human factors considerations as visibility of the material on the visual display screen in various lighting conditions, and position and posture of the computer user, the diagnostic aid used at the weapon system site becomes closely entwined with the diagnostician's task. Hence, design of a portable aid must take into account the diagnostic process, in order to allocate functions to the aid in an optimum manner. Considerations of hardware and software design to implement those functions follow.

The next generation of the CTS (often referred to as the Portable Maintenance Aid (PMA)) is planned to house diagnostic expert systems, some of which have been tested. The promise of expert systems is to make widely available the expertise of the best diagnosticians, and to reduce diagnosis time.

In developing a Portable Maintenance Aid as the next generation of the Contact Test Set, the objective is to improve human performance of the diagnostic task at the forward weapon system site. Due to the intrusive nature of the aid to the diagnostic task, the aid must be properly designed from a human factors perspective to achieve the potential of both the diagnostician and the diagnostic aid.

The Problem of Diagnostic Aiding

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A problem has been perceived in diagnostic support for complex modern weapons systems, particularly for electronic components. Each of the services has undertaken development of diagnostic aids to address this need (Demers (1989, May, Sep), Jaszka (1989)). To evaluate the design of such a device (specifically, the Army's requirement for portable testing and diagnosis at the forward weapons system site), it is necessary to understand the process of diagnosis and current research in the field of diagnostic job performance aids.

The way a diagnostic aid is developed is based upon certain assumptions about how diagnosis is or should be performed, and what types of knowledge the diagnostician needs at the job site. Job knowledge acquisition is divided between training and what is provided by the job performance aid. Hence, philosophies of training are inherent in any diagnostic aid design. Because of the interrelationships between training, personnel selection and advancement, job aid design, job knowledge and content, and job satisfaction, these assumptions inherent in the design of a job aid must be made explicit.

Unfortunately, there has been inadequate research on diagnosis itself, including how the human successfully diagnoses faults, how to best train for diagnosis, and how to select individuals who are likely to be proficient diagnosticians.

REVIEW OF RESEARCH

Knowledge:

Neiderman (1988) and Morris (1985) provide surveys of research on troubleshooting and troubleshooting aids. Field studies have also been conducted (Harz (1981), Nauta (1985), Fenwick (1982)). One of the central questions to the development of diagnostic job performance aids and training philosophies is the degree of cognitive or theoretical knowledge required by the diagnostician and the amount of

proceduralization of the job aid. Research results in this area might be viewed as contradictory or inconclusive.

For example, there have been several studies which conclude that proceduralized job aids improve performance, especially of novices. Both Neiderman (1988) and Swezey (1987) refer to a 1971 study by Elliott and Joyce, in which high school students, provided with only 12 hours of training and a highly proceduralized troubleshooting aid, equalled or exceeded the performance of experienced Air Force technicians using "conventional" troubleshooting methods. The conclusion drawn from this and similar studies is that extensive troubleshooting training is not necessary, and considerable training time and money can be saved by relying on highly proceduralized diagnostic aids instead of cognitive knowledge to solve troubleshooting problems in the field.

However, extensive proceduralization has been found to be inadequate in implementation. In an extensive review of Navy fleet maintenance problems, Nauta (1985) concluded that proceduralized training and troubleshooting aids (i.e., manuals and test equipment) left technicians unprepared to diagnose many of the faults which were encountered, resulting in a variety of ills: job dissatisfaction and stagnation, as technicians were helpless to solve many diagnostic problems and did not have the basic knowledge which would permit learning from experience; excessive consumption of components, since the only diagnostic strategy available to the technician was to substitute parts until the problem disappeared; and excessive reliance on contractors and special expert teams to diagnose equipment.

While reported research and actual experience seem to be contradictory, an explanation is available. Proceduralized aids do permit novice technicians to perform proficiently, when they are available and accurate. Experience in all the services is that traditional troubleshooting manuals have been inadequate: they are often delivered late and are full of errors, omissions, and inconsistencies. Though the quality of manuals improves over time as errors are corrected, updates are slow getting to the field, and thus manuals remain out of step with engineering changes and equipment modifications throughout the life of the system. More troublesome is the tendency of field personnel to lose confidence in inaccurate manuals, and therefore, not use them; this may be especially true of novice troubleshooters, who do not have the training or experience base which allows them to "fill in the gaps" of misleading technical information (especially if they received only procedural training).

Although improved formats for proceduralized troubleshooting aids have been investigated (Swezey (1987)), developing and validating procedures for complex equipment will remain difficult (Morris (1985) and Swezey (1987)). Proceduralized aids are also bulky and cumbersome, which can inhibit their effective use in an operational environment. More seriously, such reliance upon proceduralized aids leads to an inability to perform in the event that the aid is not available, is in error, or does not cover a situation encountered on the actual equipment. This is precisely the situation that the Navy found to exist (Nauta (1985)): Early Built In Test Equipment (BITE), designed to isolate faults among electronic components, failed to live up to expectations and design goals for the required percentage of faults to be correctly isolated. Technical manuals lacked the information the technicians needed to isolate the faults presumably handled by BITE. Navy proceduralized training (by design) did not include troubleshooting training which might have prepared the technicians to handle unexpected situations: only expected tasks were trained.

However, it is critical that weapons systems be diagnosed and repaired quickly for novel as well as 'routine' failures: it should be obvious that only failures which were expected by the design and maintenance engineers could be covered by procedures. The diagnostician must have some training to fall back on in such situations.

The solution called for by the Navy was more cognitive and theoretical training. They also undertook the EPICS (Enlisted Personnel Individualized Career System) project, to completely integrate training and personnel management of technicians, and to develop 'enriched' troubleshooting job aids which allow the technician to develop system knowledge (Smillie and Clelland (1986), Smillie (1985, 1986)). Swezey (1987) also concludes that training is necessary to prevent over-reliance on job aids. The degree to which the training should be cognitive or proceduralized has also been investigated.

Morris (1985) reports several studies which conclude that theoretical information does not lead to improved troubleshooting performance, even though technicians often indicate a desire for more theoretical and systems knowledge. Novice technicians usually cannot develop effective troubleshooting strategies from theoretical information without guidance. Research indicates that it is necessary to teach students how to use knowledge. Techniques reported by Morris (1985) include helping the student to relate a schematic to the actual equipment, instructing the student to develop a troubleshooting plan, and providing instruction on analyzing symptoms. He also reports two

simulation systems which allow practice of troubleshooting skills: the Generalized Maintenance Trainer Simulator / Electronics Equipment Maintenance Trainer (GMAT/EEMT); and SOPHIE (the SOPHisticated Instructional Environment), an intelligent interactive computer based instructional system which allows students to learn systems knowledge and practice troubleshooting problems.

There is also evidence that more experienced troubleshooters (Morris (1985)) are able to learn more readily on the job than are novices, and thus gain more transfer of knowledge from performance aids because they are able to perceive the underlying troubleshooting principles.

The reasonable conclusion is that a combination of training methods is best. The proportions will vary by technician specialty, the skill level being trained, and task requirements of specific weapons systems. Some theoretical information (principles of electronics), systems knowledge (how the system operates), and troubleshooting training (how to apply such knowledge to develop troubleshooting and testing strategies) should be provided to diagnosticians, as well as hands-on step-by-step training and practice. Even with improved on-board diagnostics (BITE), and even if proceduralized aids are available to assist the proficiency of novice diagnosticians and serve as memory aids for intermediate and experienced diagnosticians, it is unlikely that 100% diagnosis could be attained without reliance upon human problem solving in uncertain situations and for novel failures when it is necessary to reason from first principles. The diagnostician must rely upon transferrable knowledge and skills to solve problems which could not be solved ahead of time by the design of proceduralized aids.

Reasoning:

Cognitive theory (Oden (1987)) postulates that human learning and reasoning are based upon man's ability to construct mental models, which can be simulated to determine what would happen under various hypotheses. These models need not be complete or sophisticated to be powerful. An implication for the design of man-computer interfaces is that the system might have to adapt to the human's mental model. Oden concludes that work in a variety of disciplines (i.e., psychology and artificial intelligence) supports acceptance of models.

Not surprisingly, research in the domain of diagnostics supports the concept of mental models. Successful diagnosticians use a mental model of the system (based upon structure and function) to determine the logical site of a fault. According to research cited by Lee (1988), the expert is more proficient than the novice because the expert

has the ability to construct a more correct mental model of the system, and knows which model to use for different situations. The novice tends to formulate a naive mental model which may miss key functional interrelationships (Gott 1988). This explains the tendency of the novice to troubleshoot in physical proximity of the symptom, rather than the expert's (correct) approach to troubleshoot components in close functional relationship to the symptom, regardless of the physical location of those components. Lee contrasts model representations drawn by experts and novices to explain their troubleshooting strategies.

Evidence suggests that experts as well as novices may employ associative (symptom to fault) troubleshooting 'rules,' based upon experience or heuristics. But if these fail, the expert falls back upon his mental model and uses causal or 'deep' reasoning to diagnose the fault (Yoon (1988)). This solution technique must be employed for novel failures. The novice, in contrast, has an inadequate understanding of the causal relationships in the system and employs an inefficient diagnosis strategy (i.e. working backward from the location of the symptom), quickly overburdening his short-term memory (especially in a stressful situation). This leads to confusion and frustration.

Research thus explains the inability of early diagnostic expert systems to function as robustly as expected. Expert systems based upon rules alone are often brittle and fail rapidly for unexpected faults or unanticipated combinations of symptoms (Lee (1988)). Such systems mimic only the portion of the expert's approach which is based upon 'shallow' knowledge. For novel situations, the expert relies upon causal knowledge which is not available in a rule-based expert system. Experts also employ their mental models in an automatic mode after extensive experience, and may not even be able to articulate the methods they are actually employing (Gott (1988)). Traditional expert systems also cannot readily explain conclusions to the expert or novice (for validation or learning, respectively).

A powerful model methodology is described by Yoon (1988). The interface between the human and the computer is designed to solve the problem identified by Swezey (1987) for all job aids: the psychological needs of people. 'The motivational properties of leading individuals by the hand through a series of steps without requiring them to exercise their own judgement and/or logic is typically considered demeaning... Job aids must be designed in a fashion that alleviates the feelings (of) job incumbents that they are merely 'trained monkeys' who are qualified only to perform the simplest tasks.' This approach is especially insulting when the human's tasks are directed by the computer' Yoon (1988)

points out that traditional expert systems often use a computer-directed serial interaction. Not only does this prevent the human from employing any strategy of his own, but the serial nature of the interaction interrupts his information processing, preventing deep reasoning. As discussed above, traditional diagnostic expert systems typically fall short in novel situations. A directed interface reinforces that failure by discouraging human problem solving. Yoon suggests an independent or suggestive form of interaction based upon the philosophy that the system should provide support for the human's information processing needs: to prevent cognitive and short-term memory overload, and to overcome well-documented tendencies of human problem solvers to under-specify the hypotheses set (based upon cognitive limitations) and to fail to incorporate negative evidence. This is a different philosophy than that of many current systems, which presume the system to perform the diagnosis in conjunction with symptom information and test observations provided by the human. Not only is this potentially unsatisfying, the operator will not develop diagnostic skills that may become necessary when the automation fails (Yoon (1988)). This realization is fully consistent with the conclusions regarding diagnostic knowledge and training requirements.

Thus, the design of diagnostic job performance aids requires creativity and attention to the human interface. Some provision for automatic diagnosis will be necessary: for example, to reach a conclusion on-board without the need for skilled technicians; to ensure the proficiency of novice technicians; or to save diagnosis time, especially in stressful situations of fatigue or time pressure, when the priority for getting the system operational as fast as possible mitigates the technician's desire to control or learn from that particular diagnostic session. However, the diagnostic aid must be designed for learning and explanation as much as for internal diagnostic reasoning.

The recent trend in the development of diagnostic systems is to employ causal models of the system at one or more levels of abstraction. Not only is such an approach appealing in that it might 'model' the way a human diagnostician sees the device (hence, a consistent model sharing between the diagnostic software and the human), it also allows natural explanation and training. BBN (Feurzig (1988)) has developed a system which can teach electrical systems troubleshooting theory and perform diagnosis using a model of the system with qualitative reasoning. The system has a model of the student (level of experience, etc.) and a model of the domain. It also helps the student to develop his own model of the domain and knowledge which is transferrable from one diagnostic situation to another. As suggested by

Yoon (1988), one method of interaction between human and system is for each to follow an independent diagnostic strategy. A causal model can be simulated qualitatively to predict system functioning or to compare normal and observed system behavior to isolate a faulty portion of the structure. Yoon's research shows that such information is compatible with the human's reasoning process. Model-based systems are superior for automatic diagnosis because they are not limited to symptoms or faults which were anticipated (as are rule based systems), but can reason from the model in novel situations. Another advantage of models is the potential to use the CAD model of the system generated at design time, saving expensive software development.

OTHER DIAGNOSTIC AID DESIGN CONSIDERATIONS

The conceptual framework for diagnosis aiding, based upon the above research, provides the basis for evaluating function allocation between man and machine (aid), and the man-machine interface. To assess the ability of the aid to function in the operational environment, attention to the design of hardware is necessary. Novel (as well as existing commercial) implementations should be explored, based upon current developments in the fields of natural language understanding and voice recognition (Simpson (1985), Hauptman (1988), Jones (1989), Leiser (1989), Martin (1989), Swezey (1987)), human-computer interfaces (Farooq (1989), Morrison (1988), Shneiderman (1988)), display devices such as virtual images (Newman (1980, 1984, 1987, 1987a)), and paper versus electronic delivery (Smillie (1988), Nugent (1987)). Swezey (1987) reports on projects undertaken in voice and virtual image interfaces which have potential to free the technician's hands.

Expectations for the portable maintenance aid are likely to meet with disappointment, unless concurrent improvements in other areas which affect system diagnostic performance are also made (Nauta (1985)). The biggest factor affecting diagnostic performance is the design of the weapons system itself. Although this is not a variable which can be altered for existing weapons systems, it is vital that such relationships be understood, and that computer-based maintenance aids not be perceived as a solution for more systemic problems.

CONCLUSIONS

Research Issues:

Further research is required; however, the perceived need for immediate assistance and the advertised availability of solutions dictate that diagnostic aids will be developed and implemented before the domain is fully understood. This is

to be expected, but, the warning of Morris (1985) must be heeded: "accompanying this trend toward greater use of technology, there seems to have been a shift in emphasis that avoided, whether purposefully or incidentally, an evaluation of transfer of training. All too often recent 'experiments' have been demonstrations rather than evaluations. Research should retain as its primary goal the evaluation of transfer to real-life situations."

In addition, earlier research on troubleshooting is often based upon a number of students identifying faults in a diagrammed network, leading to conclusions about proceduralization and level of cognitive skills necessary to perform troubleshooting. While many of these experiments used valid scientific techniques, they do not usually take into account the real world, where errors in proceduralized aids are possible, and where systems are so complex that such problems might be considered as "toy" - i.e. results might not be transferrable.

While it is possible to make informed conjectures from existing research, it is not yet known what level of cognitive skill is necessary for diagnosis and how it should be provided. (Readers are recommended to the Neiderman (1988) and Morris (1985) surveys to judge for themselves the implications of the limited and sometimes contradictory research results that are presently available).

Design Problem:

The problem in diagnostic job aiding, then, is to develop a diagnostic framework consistent with human reasoning methods and cognitive limitations, and to design diagnostic information aiding within that framework by parceling job knowledge requirements among training (human long term memory), human short term memory, and the diagnostic aid. The literature supports the conclusion that model-based approaches are the most natural and potentially the most supportive of both the human diagnostic process and diagnostician learning, as well as offering the most powerful approach for machine-independent diagnosis (when necessary or desirable). Designing the diagnostic job performance aid begins with these decisions. Hardware and software to house and deliver information aiding must then be designed to meet the operator's needs in the operational environment. Design principles from a variety of technical disciplines must be considered.

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